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# A Methodology for Managing Complexity

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**Abstract.** In this work complexity is defined as the combination of the number and types of Value Transfer Functions (VTF) between stakeholders of a system. Increasing the number of stakeholders increases the complexity. The two primary objectives of management of the complexity are to (i) reduce the uncertainty of estimating project schedule and budget, and (ii) improve the performance of the team. Managing the complexity is both an art and a science. Whereas the art refers to “best management practices,” the science lacks an inadequate theory and measures. In this exploratory work, a methodology to manage the complexity is developed, which couples massively Parallel Critical Chains (PCP) and Program Evaluation and Review Technique (PERT). Specifically, each chain in PERT is reduced to its critical path and all chains are then reconstructed into a parallel set of massively interdependent critical paths. Each task is buffered in time from its input and outputs with short subtasks that serve to start coordinate, and handoff the necessary information and resources required for the completion of the task.

## INTRODUCTION

The execution of a system development or sustainment program or project is assessed not only in terms of the performance of the fielded system, but also in terms of management’s ability to contain the system development cost and to adhere to the development schedule. The ability to stay within the planned schedule is related to the ability to reduce uncertainty in the schedule.

Among the factors contributing to the schedule uncertainty is foremost the management of complexity of the work environment. Complexity stresses the constructs of modern management techniques and systems engineering practices. Complex systems have a great variety of interactions, which transcends physical, information, and social interfaces.

It is generally observed that some of the many traditional approaches to managing development and sustainment activities are indeed effective in delivering simple projects that have permissive schedules, adequate budgets, and well defined requirements. The U.S. Department of Defense mandates systems engineering to be employed in the development of advanced weapon systems under the Defense Acquisition System Directive (2003)). However, whereas literature on systems integration abounds, integration of systems engineering and its best modern practices with a technical management methodology has not been articulated, especially when dealing with complexity. Gandara (2000) describes the recent test experience by the U.S. Air Force Operational Test and Evaluation Center (AFOTEC), and Bierstine (2002) discusses the new processes to assist the U.S. Air Force Flight Test Center

(AFFFTC, 2002) with development and sustainment projects. These as well as references cited at the Theory of Constraints (TOC) conference (2004)—Pratt and Whitney (U.S.), The Boeing Company (U.S.), Honeywell Defense and Space Electronic Systems (U.S.), Sumino (Japan), Gray-Syracuse, ESCO Turbine Technologies (U.S.), Eastern Financial Florida Credit Union (U.S.), BAE Systems (U.K.), Lockheed Martin Corporation (U.S.), General Motors (U.S.), Delphi Corporation (U.S.), Indo Asian Fusegar Limited (India), and Suntory (Japan)—strongly suggest that critical chain project management (CCPM) combined with systems engineering would be needed to effectively deal with complexity. In CCPM the effectiveness of information transfer from one task to another measured, as the handoff between tasks is constructed and enacted according to the nature and whims of the affected individuals, often without formal procedures. There is thus no objective measure of the transfer of information in CCPM. The concept of a VTF is formulated in this paper precisely to make such measurement.

Whereas the U.S. DoD has adopted standards, widely practiced methods and system development models, systems development programs still have great latitude to customize and adapt to various constraints and propensities. There is thus much uncertainty in the measurable effectiveness of systems engineering in programs. Programs and projects continue to fall behind schedule, exceed cost, and fail to deliver the intended requirements. It is conjectured that such quandary is due to some deficiencies in the current formulation of systems engineering. It is also conjectured that redacting of system engineering is needed to overcome the deficiencies. Research has been carried out

(Langford 2006, 2007) and will continue in an attempt to achieve such an objective.

The anticipated consequences of redacting systems engineering are to (i) clarify the nomenclature to improve communications between stakeholders, (ii) merge new constructs that extend the methodology to provide better outcomes (on-schedule, on-budget, and on-requirements delivery), and (iii) incorporate a structure that better integrates lifecycle issues with architectures that are more responsive to changes during development and sustainment.

In this paper we concentrate on these three ideas. A companion paper (Huynh and Langford, 2008) will deal with a rigorous mathematical foundation of the methodology.

The remainder of the paper is organized as follows. We first explain the proposed changes to the systems engineering. We then follow with a discussion of the methodology to manage complexity. We continue with an elaboration on how the redacted systems engineering supports the methodology. Finally, we demonstrate how the methodology aids in reducing schedule uncertainty. We then end with some concluding remarks.

## **PROPOSED ENHANCEMENTS TO SYSTEMS ENGINEERING**

The redacting of systems engineering centers on redefining and restructuring many of the fundamental terms commonly used. We focus on the following constructs: system, value, function, value transfer function (VTF), and complexity.

**System.** A system is a set of elements that are either dependent or independent but interacting pairwise—temporally or physically—to achieve a purpose. The elements form the boundary of the system. This definition takes into account both the permanent and episodic interactions among

elements of a system or systems of a system of systems. It thus includes the lasting and occasional interactions, as well as emergent properties and behaviors, of a system. These interactions effect transfer of energy, materiel, data, information, and services. They can be cooperative or competitive in nature, and they can enhance or degrade the system value, which is defined below. The pairwise interaction transfers a measure of worth from one element of a pair to the other element. We term the measure of the transferred worth the Value Transfer Function (VTF), which will be discussed below.

**Function.** We define the worth of a system (or product or service) in terms of the system functions, their performances, and their qualities. For example, a product shall provide a function with specified performance and a delimited level of quality. A function is an action performed by the system that is required to achieve a system objective. System functions may change and be added or deleted. The concepts of performance and quality of a function will be elaborated in the following discussion.

**Value.** Value (V) is defined as the ratio of worth (W) to investment (I). Value compares what one receives with what one has invested (Langford 2006). If there are two products with factually comparable features offered for different prices, the value of the lower-priced product is higher than that of the other product. The value of a system is measured by its worth (the actual and expected use of a product or service) relative to the investment made in obtaining the system. The system value may vary with time. To account for additional investments made during the system lifecycle, the investment can also change with time.

The worth (or equivalently, the use) of a product or service can be represented by the functions and their related functional attributes – performance and quality. As in (Langford, 2007), the system value,  $V(t)$ , is given by

$$V(t) = \frac{\sum F(t)P(t)Q(t)}{I(t)} \quad (1)$$

where  $F(t)$  is a function performed by the system,  $P(t)$  is the performance measure of the function  $F(t)$ ,  $Q(t)$  is the quality, which is the tolerance assigned to  $P(t)$ ,  $I(t)$  is the investment (e.g., dollars or other equivalent convenience of at-risk assets) and the time,  $t$ , is measured relative to the onset of initial investment in the project. We refer to the delineation of a function in terms of its performance and the quality of the performance as the triadic decomposition of the function. If the unit of  $Q(t)$  can be converted to the unit of  $I(t)$ , then the unit of  $V(t)$  is that of  $P(t)$ , since  $F(t)$  is dimensionless.

Performance indicates how well a function is performed by the system. In this work, quality refers to the consistency of performance (or tolerance that signifies how good the performance is) in reference to the amount of pain or loss that results from the inconsistency as described by Taguchi (2005). In essence, functions result in capabilities; performances differentiate competing products; and quality affects the lifecycle cost of the product. For each function, there is at least one pair of requirements — performance and quality. The quality requirement indicates the variation and impact of the variation of the performance requirement of a function. A system function may thus have different values of performance and the quality of a performance may have different values. The summation in (1) is thus over all values of the functions, performance, and quality.

Several schemes have been proposed to define and structure requirements, such as functions, performance, and tolerances/physical synthesis by Wymore (1993), hierarchical task analysis by Kruchten (2000), decomposition coordination method of multidisciplinary design optimization by Jianjiang (2005), functional descriptions by Browning (2003) and Cantor (2003), and non-functional descriptions by Poort (2004). The functional triadic decomposition proposed in this work forms a basis for a management tool that provides a structure to control the project. Again, triadic decomposition prescribes that every function is imbued with the necessary and sufficient attributes of performance and quality. It forms a basis for a management tool that provides a structure to control the project.

Control centers on three functions (again, each with associated performance and quality): Regulate (monitor and adjust); govern (define limits, allocate resources, determine requirements, and report); and direct (lead, organize, and communicate).

Traditional functional analysis, supplemented with the triadic decomposition, is conjectured to result in a complete and comprehensive set of requirements. The resulting functional decomposition, together with commensurate system specifications and the mechanisms of action or activity (e.g., creation, destruction, modulation, translation, transduction), should form a basis upon which a system can be designed and built using the classical set of system development models, such as the spiral, “Vee”, and waterfall model.

The value of a product is thus quantified according to (1). From the manufacturer’s point-of-view, a “value product” is one that has met some investment criteria for the desired set of functionality, performance, and quality requirements. From the consumer’s point-of-view, the expression in

(1) aids in the trade between the applicability of a purchased product (in terms of the item’s functionality, performance, and quality) and the total cost and time invested in the purchase and use of the product.

Value is calculated at the moment of exchange of worth for a given investment – the moment of the purchase/sale of a product or service. Value is simply the price one pays for the product received, or, alternatively, the amount one receives in payment for the product provided. These exchanges (or interactions between elements) are quantifiable and may have a net impact on the value of the system or both systems in the case of a system of systems. A net impact is a consequence that exceeds a threshold of interest as discussed with Kujawski (2007).

**Value Transfer Function.** In control theory, a transfer function is a mathematical representation of the relation between the input and output of a system. A value transfer function (VTF) between two elements of a system is defined to be the exchange of value between the two elements. Value is what is received (in terms of usefulness) for an investment. This exchange necessarily assumes some measure of risk. Given risk, a VTF can thus be either a manifestation of the state, (or a change in state of a system) or a tool to evaluate differences between the state of a system and the state of another system or between the states of two systems in a system of systems. In essence, the VTF represents various impact(s) on the state(s) of a system. The VTF can be a nested hierarchy of VTFs, all related through functional decomposition. Depending on the value ascribed to each of the VTFs, the state(s) of the system(s) may be impacted to varying degrees. The result is that a small number of VTFs may be equivalent to a large number of irreducible VTFs.

A VTF can be a nested hierarchy of VTFs, all related through functional decomposition. A small number of highly decomposable VTFs may be equivalent to a large number of irreducible value transfer functions.

**Complexity.** Complexity of a system is often characterized by the total quantity of units that make up the system. As described by Homer (2001) and Li (1997) it is both the number of and interactions among the units that in general are used to imply and define complexity. The system complexity thus augments the management challenge because of the large number and various types of system elements and stakeholders. In this work, complexity is reflected by the number and types of VTFs among the elements of a system or among the systems of a system of systems. Since an element of a system may also be a stakeholder of the system, increasing the number of stakeholders increases the complexity. Managing complexity or managing stakeholders thus amounts to managing the VTFs. It must be noted that a stakeholder with a large VTF (i.e., a funding source with many requirements) may add no more complexity than does a large number of stakeholders with a few requirements.

**Risk.** Using the logic in (Lowrance, 1976), Lewis (2006) defines simple risk as a function of three variables: threat, vulnerability, and damage. Replacing damage with value, Langford and Horng (2007) capture risk through threat, vulnerability, and value. An element  $e$  of a system is associated with a risk,  $R_e$ , defined by

$$R_e = X_e U_e V_e = X_e (1 - a_e) V_e \quad (2)$$

where, threat,  $X_e$ , is a set of harmful events that could impact the element; vulnerability,  $U_e$  is the probability that element  $e$  is degraded or fails in some specific way, if

attacked; value,  $V_e$ , results from a successful attack on element  $e$ ; and susceptibility,  $a_e$ , is the likelihood that an asset will survive an attack.  $V_e$  is given by (1). It may be loss of productivity, casualties, loss of capital equipment, loss of time, or loss of dollars. Susceptibility is the complement of vulnerability.

Since an element in a system (or network) may be connected to more than one element, the number of VTFs associated with the element is the degree of the element. Subscribing to Mannai and Lewis (2007), we obtain the system risk,  $R$ , as

$$R = \sum_{i=1}^{n+m} X_i (1 - a_i) g_i V_i \quad (3)$$

in which  $n$  denotes the number of elements,  $m$  the number of links or VTFs, and  $g_i$  denotes the degree of the  $i^{th}$  element.

As a result of the VTF between two elements,  $e_1$  and  $e_2$ , at the moment of their interaction, we have

$$\frac{V_{e_1}}{R_{e_1}} = \frac{V_{e_2}}{R_{e_2}} \quad (4)$$

It is the expression in (4) that forms the basis for complexity management.

## SUSTAINMENT MANAGEMENT

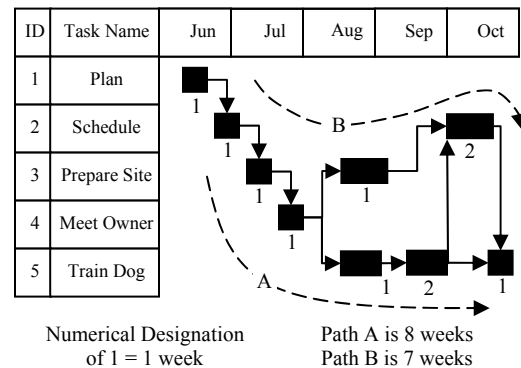
A successful sustainment should be measured by its variance from the original commitments for satisfaction of scope and requirements (due date and budget). The effectiveness of management through the use of tools, mechanisms, processes, and procedures, coupled with concerted effort of labor, may be ineffectual in sustainment management (i.e., achieving a prolonged and desired level of sustainment.) It is the combination of commitments and limitations of resources that challenges the success of often simultaneous, multiple projects. Since sustainment is an integration of activities,

linked through partnerships, knowledge, and strategy, strong leadership and a sound methodology are required. Leadership transfers risk and control, but not without the commensurate accountability, measurement, and risk management. Methodology is the engine of action that sets the work in motion. The functions of management (e.g., planning, organizing, directing, controlling, communicating, and team building) deal generally with the variables that determine capability, but the determination of what path to follow is equally important. The capability includes maintaining, fielding, improving, supporting, managing, converting, extending lifetime, altering, removing, and disposing.

At issue is how to deal with changes in requirements. The challenges posed by the dynamics of a system demand frequent and sometimes substantial changes in the complexity of a system. The addition or deletion of elements or changes in the types of interactions between elements result in changes in the VTFs associated with these system elements. Tracking and understanding of the implications of these changes strain conventional management ability. A common management practice involves the use a network scheduling tool (e.g., Program Evaluation and Review Technique (PERT)) combined with Critical Path Management (CPM)). The combination PERT/CPM seemingly addresses the concerns of scheduling and tracking tasks. A typical PERT/CPM project plan is illustrated in Figure 1, which is discussed in the following discussion.

**Management Methodologies.** There are at least two underlying philosophies of managing a project – manage the task and manage the flow. Task management is the traditional means using GANTT and CPM/PERT. On the basis of completion date of each task and its impact on the overall schedule, the project manager

following task management makes decisions and takes action.



**Figure 1.** Typical PERT/CPM Project Plan

Flow management is the premise for critical chain project management. In contrast to ‘managing the task’, ‘managing the flow’ concentrates on the relationships between tasks and difficulties in transferring value via a VTF. In essence, managing of the flow is the same as managing of the VTFs between system elements.

In Figure 1 the major task names are indicated along with a designation (an identification number (ID)) that identifies the tasks and facilitates tracking of time and expenditures. The leading edge, trailing edge, and length of the solid rectangles indicate the beginning time for the task, the ending time for the task, and the duration of the task, respectively. Beginning and ending dates are often added to these rectangles, in addition to the number of people, the person responsible for completing the task, and their budget. In this case the numerical designation found below the solid rectangles indicates the number of weeks (e.g., 1 means 1 week). The tasks along Path A are expected to be completed in eight weeks, versus Path B in seven weeks. The alternative Path B that loops upwards into Path A adding an additional two weeks to Path B is rejected, leaving only Path A and Path B. Path A is the critical path. A critical

path is a sequence of actions that take the longest time to complete. By definition, a delay in any task within a critical path is a delay in the delivery of the project.

CPM/PERT requires clearly defined tasks that are independent and unchanging. In addition, the antecedence kinships must be defined for all tasks. Mixing level-of-effort tasks and newly defined and undefined tasks using PERT/CPM therefore denies visibility and accountability of the connectivity of these tasks. For an sustainment effort of less than a dozen tasks (elements) and associated VTFs (e.g., manager, transportation, open-air field, weather, dog trainer, one dog, and the dog's owner), the manager can effectively schedule a brief training activity. For complex projects involving a myriad of activities, automation has helped reduce the managerial task, but the benefit of seeing the sequence of tasks that need to be done remains.

The details of the task sequence and the interaction of the tasks often defy discovery of interface and transfer difficulties, inadequate acknowledgement of the risks associated with individual tasks, and the extent of the impacts of a single task on emergent risks. Without proper identification and analysis, the number and kinds of VTFs between elements induce far too many variables to track, thereby mitigating the simplicity of calculations and graphical utility used to display status and monitor interactions.

Sustainment must be enacted in a methodical and smooth, politic manner to avoid starts/stops, missteps, and consequential and collateral losses. Both leadership and better tools are necessary.

**Schedule Uncertainties.** To achieve success in managing complexity, a solution is to apply a well-structured network scheduling tool that exerts the good qualities and simultaneously improves the capability of

CPM/PERT to deal with complexity, task antecedences, and task kinships. However, an effective handling of changes to requirements, unreliable estimates of task completion dates, and task interdependences requires an alternative solution. An attempt at the alternative solution is proposed here. It is a structured consideration of the concepts of value, risk, and VTFs espoused here, which are used to form a foundation of successful management and sustainment. We argue that complexity is manageable if it is seen through an examination and assessment of VTFs.

### **Critical Chain Project Management.**

Critical Chain Project Management (CCPM), proposed by Goldratt (1977), acknowledges risk as a normal consequence of management and incorporates a process to recognize and manage it. Instead of estimating the duration of each task and applying an overall management reserve to accommodate risk, CCPM estimates and allocates time, cost, and resource to each task for identified associated risks. A task is concatenated with its predecessor task(s) that provide its inputs and with the successor task(s) that require its inputs. In this way, the tasks are linked to form chains — chains of events. The objective of CCPM is to build as many tasks as possible that form critical event paths, critical chains of events in which (i) there is no waste time, money, or resources per task, and (ii) the project critically depends on the completion of the chain of events. A critical path is a sequence of actions that take the longest time to complete. By definition, a delay in any task on a critical path is a delay in the delivery of the project. A critical chain is defined as the longest chain of dependent events; the dependency is related to either a task or an asset. The critical chain is the critical path with schedule buffers preceding and trailing in time.



**Massively Parallel Critical Chain Management.** To handle the issues of modifications and additions of tasks, underrepresented work efforts, and non-uniform prediction of schedule or schedule bias, the non-critical paths are buffered with shadow tasks that are not staffed and unfunded. The shadow tasks used to fill out the schedule network turn every chain of tasks into a critical chain resulting in

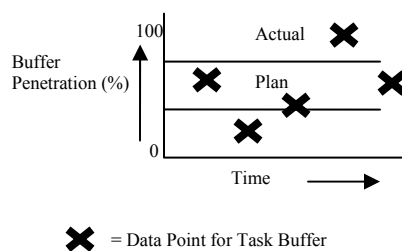


depiction of parallel critical tasks. Implementation of the massively critical chain project management (mCCPM) requires four practices:

- Interruptions and additional work that challenge the deliveries of tasks are either procedurally relegated to level-of-effort activities by staff or formalized into tasks outside of the existing critical chains. Best practice indicates

- <sup>1</sup> Successful applications of mCCPM from 1994 to 2005 by the first author in support of the development of the U.S. Air Force TR-1 Ground Station; spacecraft design for NASA Ames Research Center; development of an Internet consumer appliance; and delivery of enterprise software to support an online healthcare service.

As with MCPM, risk is accounted in the tasks by building buffer tasks on the input and output sides. The input buffer is set by the uncertainties of the predecessor, and the output buffer is set by the uncertainties of the task itself. Each task thus has an input and output buffer. Figure 3 illustrates a means of tracking the percentage of usage of buffers. Each buffer can be analyzed and the lessons learned can be incorporated in subsequent task planning on the same as well as future projects.



**Figure 3.** Plot of temporal trends of buffer penetration.

Within the first one-third of usage of the buffer, the manager observes. Within the middle third of the buffer, the manager and the task lead determine the reason for the use of buffer time and develop a plan for action including decisions and decision points. Within the final third of the buffer, the manager must carry out the action(s). This massively critical chain technique would reduce the amount of expected uncertainty in performing tasks (see footnote 1). Massively critical chain thinking could extend the premise of critical chains to the ‘more is better’ extreme case. In this regard, more critical chains indeed reduce the waste and uncertainty of management (U.S. Navy, 2006).

Value and risk are essential measures of VTFs and mCCPM. The general construct of Value/Risk for the act of managing as well as the results of managing (whether it is for product development or sustainment)

delivers a process-model view for managing in a complex environment.

**Conclusion.** In this paper a methodology to manage complexity is sketched. It results from integrating the massively parallel critical paths method and the systems engineering constructs espoused in this paper. This methodology establishes a set of measures that can be tracked, evaluated, and reported. The result is an understanding of the sensitivities of relationships between the WBS elements and the schedule. With this understanding, the manager can begin to answer the two key questions: Where do I spend my next management money and when do I spend my next management hour?

Again, in this paper we concentrate on the ideas. A companion paper (Huynh and Langford, 2008) will deal with a rigorous mathematical foundation of the methodology for complexity management.

## BIOGRAPHIES

**Gary Langford.** Lecturer, Naval Postgraduate School in Monterey, California. His research interests include Systems Engineering theory, complexity theory, and management theory. His teaching includes courses in Systems Engineering, Systems Engineering Project Management, and the Economics of Product Development. Mr. Langford has founded and run five corporations – two venture-backed, and one Nasdaq listed. He was Executive Vice President of Castle, Overmyer, Poole, and Schubert (COPS International), a merchant bank. Mr. Langford is a former NASA Fellow. He earned an A.B. in Astronomy from UC Berkeley and an M.S. in Physics from then Cal State University, Hayward. Mr. Langford has advised the government of South Korea in matters of education and market analysis; and the U.S. government in

matters of social policy and scientific matters.

**Tom Huynh** is an associate professor of systems engineering at the Naval Postgraduate School in Monterey, CA. His research interests include uncertainty management in systems engineering, complex systems and complexity theory, system scaling, simulation-based acquisition, and system-of-systems engineering methodology. Prior to joining the Naval Postgraduate School, Dr. Huynh was a Fellow at the Lockheed Martin Advanced Technology Center, where he engaged in research in computer network performance, computer timing control, bandwidth allocation, heuristic algorithms, nonlinear estimation, perturbation theory, differential equations, and optimization. He was also a lecturer in the Mathematics department at San Jose State University. Dr. Huynh obtained simultaneously a B.S. in Chemical Engineering and a B.A. in Applied Mathematics from UC Berkeley and an M.S. and a Ph.D. in Physics from UCLA.

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